

# A Broad-Band Phase-Contrast Wave-Front Sensor

The intrinsic  $90^\circ$  phase shift of an ideal beam splitter would be exploited.

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A broadband phase-contrast wave-front sensor has been proposed as a real-time wave-front sensor in an adaptive-optics system. The proposed sensor would offer an alternative to the Shack-Hartmann wave-front sensors now used in high-order adaptive-optics systems of some astronomical telescopes. Broadband sensing gives higher sensitivity than does narrow-band sensing, and it appears that for a given bandwidth, the sensitivity of the proposed phase-contrast sensor could exceed that of a Shack-Hartmann sensor. Relative to a Shack-Hartmann sensor, the proposed sensor may be optically and mechanically simpler.

As described below, an important element of the principle of operation of a phase-contrast wave-front sensor is the imposition of a  $90^\circ$  phase shift between diffracted and undiffracted parts of the same light beam. In the proposed sensor, this phase shift would be obtained by utilizing the intrinsic  $90^\circ$  phase shift between the transmitted and reflected beams in an ideal (thin, symmetric) beam splitter. This phase shift can be characterized as achromatic or broadband because it is  $90^\circ$  at every wavelength over a broad wavelength range.

The phase-contrast approach was originally devised by Frits Zernike for microscopy as a means of obtaining intensity images from such phase objects as transparent biological samples. Figure 1 schematically illustrates an adaptation of the phase-contrast approach to real-time wave-front sensing for adaptive optics. The incident light from a guide star can be described in terms of a pupil field function  $A \exp(i\phi)$ , where  $A$  is an aperture function that expresses the effect of the shape and size of the telescope pupil and  $\phi$  is the difference between the actual instantaneous phase and the nominal (e.g., plane-wave) phase of the wave front at a given position within the pupil. If the pupil were simply re-imaged, the phase signal would not normally be observable. To make the phase signal observable, one reasons as follows:

Assuming a small-signal approximation ( $\phi \ll 1$ ), the phase part of the pupil field function could be approximated as  $1 + i\phi$ . Hence, the phase-difference (diffracted) component would be  $90^\circ$  out of phase with the larger undiffracted component. To a first approximation, the un-

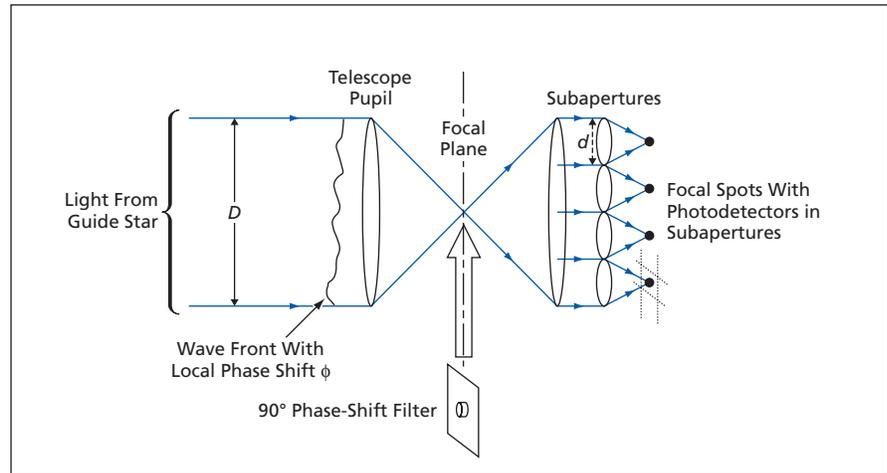


Figure 1. Phase-Contrast Imaging would use  $90^\circ$  phase shifting to generate phase feedback for adaptive optics.

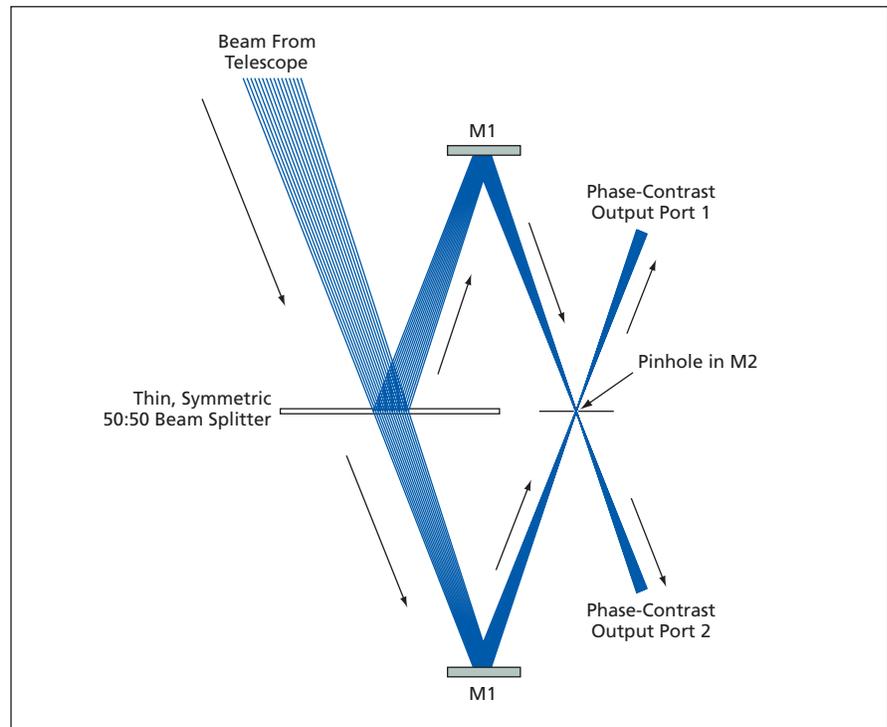


Figure 2. A Broad-Band Phase-Contrast Wave-Front Sensor, shown here schematically, can be realized by using the intrinsic properties of a beam splitter to give an achromatic  $90^\circ$ -phase-shifting element.

diffracted rays would be localized within the central  $\approx \lambda/D$  portion of the telescope focal plane (where  $\lambda$  is wavelength and  $D$  is the diameter of the primary mirror or lens of the telescope), while the diffracted rays that contribute to the phase component would impinge on the telescope focal plane at off-axis positions. If a  $\pm 90^\circ$ -phase-shift filter (e.g., a dielec-

tric disk of suitable thickness) having approximately the diffraction-limited size  $\lambda/D$  were placed at the focal point, then the undiffracted component would be shifted by  $\pm 90^\circ$  and would thereby be brought into phase (or phase opposition) with the diffracted component. As a result, the phase component would become observable as a small variation in

intensity across the pupil, superposed on the bright, uniform illumination of the undiffracted component. In the small-signal approximation, the total intensity in the re-imaged pupil would be proportional to  $1 \pm 2\phi$ , the sign of  $2\phi$  depending on whether the focal-spot filter advances or retards the phase.

Figure 2 schematically illustrates an optical assembly, according to the proposal, for implementing the  $90^\circ$ -phase-shift filter needed in a phase-contrast sensor like that of Figure 1. An incident beam from a telescope would strike a 50:50 beam splitter. The reflected and transmitted beams would be recombined by an arrangement of mirrors, schematically represented by flats M1 in Figure 2; one

component is directed through a diffraction-limited pinhole in two-sided mirror M2. The pinhole would pass the central  $\approx \lambda/D$  portions of the beams, while the M2 surfaces surrounding the pinhole would reflect the off-axis portions. The total beam going to the output port on each side of M2 would comprise the desired combination of central rays and  $90^\circ$ -shifted off-axis rays. The output beams could be directed into telescope-pupil-reimaging optics equipped with a charge-coupled-device (CCD) or similar quantum detector, as in Figure 1. Optionally, the phase-contrast images contained in both beams could be combined optically or electronically to increase the signal-to-noise ratio.

*This work was done by Eric Bloemhof and J. Kent Wallace of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).*

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## Progress in Insect-Inspired Optical Navigation Sensors

Some details of implementation have become available.

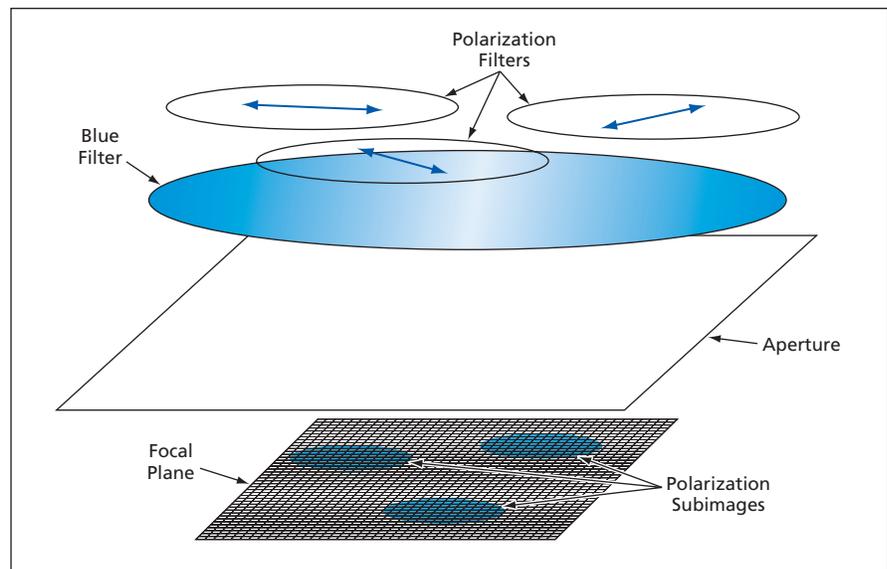
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Progress has been made in continuing efforts to develop optical flight-control and navigation sensors for miniature robotic aircraft. The designs of these sensors are inspired by the designs and functions of the vision systems and brains of insects. Two types of sensors of particular interest are polarization compasses and ocellar horizon sensors.

The basic principle of polarization compasses was described (but without using the term "polarization compass") in "Insect-Inspired Flight Control for Small Flying Robots" (NPO-30545), *NASA Tech Briefs*, Vol. 29, No. 1 (January 2005), page 61. To recapitulate: Bees use sky polarization patterns in ultraviolet (UV) light, caused by Rayleigh scattering of sunlight by atmospheric gas molecules, as direction references relative to the apparent position of the Sun. A robotic direction-finding technique based on this concept would be more robust in comparison with a technique based on the direction to the visible Sun because the UV polarization pattern is distributed across the entire sky and, hence, is redundant and can be extrapolated from a small region of clear sky in an elsewhere cloudy sky that hides the Sun.

Three different implementations of a polarization compass are under consideration. Each implementation offers distinct advantages and disadvantages relative to the others:

- In the lightest and least power-consuming implementation, the polariza-



**Three Differently Oriented Polarization Filters** are used in projecting subimages on a CMOS image detector. In addition, a short-wavelength-pass (blue) filter contributes to image contrast because the polarization signal is strongest in blue light.

tion in the sky is sampled in, typically, 10 fields of view, each centered on a different direction and having an angular width between  $10^\circ$  and  $20^\circ$ . An eight-bit microcontroller suffices to do all required data processing. A production version of a sensor according to this implementation could be self-contained. One disadvantage of this implementation, as determined in experiments performed thus far, is that bearing accuracy is characterized by an uncertainty of about  $2^\circ$ . Another disadvan-

tage is that this sensor cannot be used for imaging.

- In the second implementation, three differently oriented polarization filters are used to produce three subimages of the sky scene in separate focal-plane areas of a complementary metal oxide/semiconductor (CMOS) video camera (see figure). This implementation is amenable to sophisticated processing of polarization-image data and possible sub-degree accuracy in determining the relative angular position of the Sun. Unfortunately, for a